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USE OF THREE ISOTOPES TO CALIBRATE HUMAN BONE RADIOCARBON DETERMINATIONS FROM KAINAPIRINA (SAC), WATOM ISLAND, PAPUA NEW GUINEA

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ABSTRACT. In archaeological dating, the greatest confidence is usually placed upon radiocarbon results of material that can be directly related to a defined archaeological event. Human bone should fulfill this requirement, but bone dates obtained from Pacific sites are often perceived as problematic due to the incorporation of ^{14}C from a range of different reservoirs into the collagen via diet. In this paper, we present new human bone gelatin results for 2 burials from the SAC archaeological site on Watom Island, Papua New Guinea, and investigate the success of calibrating these determinations using dietary corrections obtained from $\delta^{34}S$, $\delta^{15}N$, and $\delta^{13}C$ isotopes.

INTRODUCTION

There are relatively few early Pacific archaeological sites with human remains (Kirch et al. 1989; Pietrusewsky 1989). Consequently, those remains that have been found are important to the understanding of change over time in burial practices, economy, and the relationships between different populations. Direct dating of these human bones should provide the most secure means of establishing the age of burials, especially in sites where later activities have disturbed the deposits or few datable cultural remains have been found in association. Radiocarbon determinations on human bone protein have, however, often produced ^{14}C results that are at odds with cultural remains (Spriggs 1990:6; Anderson and Clark 1999:36).

It is now apparent that ^{14}C results of human bone protein may be different than expected because of the consumption of marine, freshwater, and terrestrial plants and animals. It has long been known that stable isotopes provide an indication of past human diets, and $\delta^{13}C$ and/or $\delta^{15}N$ isotopic values are currently being used as a quantitative measure of different dietary sources for ^{14}C calibration (Lanting and van der Plicht 1998; Arneborg et al. 1999; Cook et al. 2001, 2002; Schulting and Richards 2002; Bonsall et al. 2004). In general, the success of these calibrations appears to be dependent on the complexity of the diet. Recently, Bayliss et al. (2004) compared the methodologies of Arneborg et al. (1999) and Ambrose (1993:83) using $\delta^{13}C$ and/or $\delta^{15}N$ values, to determine the likely foods eaten by the inhabitants of medieval Timberhill in Norwich. In this instance, each method resulted in different interpretations of the data and significantly different estimates for the chronology of the site (Bayliss et al. 2004:573). This variation could be due to the parameters used as well as the complexity of a diet that, on the basis of archaeological evidence, was dominated by marine foods, low levels of freshwater fish, and legumes. Environmental, physiological, and biochemical processes may also be a factor (Ambrose 1993:85; Ben-David and Schell 2001:183).

Calculating a suitable dietary correction for ^{14}C dates of human bone from the Pacific is especially complex because of a possible combination of marine, reef, and freshwater foods, and C_3 and C_4 plants. In particular, nitrogen fixation in coral reefs results in lower $\delta^{15}N$ values in organisms that subsist in this environment, with some being as low as terrestrial animals (Schoeninger et al. 1983: 220). Similarly, differences in carbon fractionation for C_4 plants (e.g. sugarcane) result in $\delta^{13}C$ values that are more positive and difficult to distinguish from marine values. Recognizing this problem for dietary reconstruction, Leach et al. (1996) used a third isotope, $\delta^{34}S$, and developed a computer

simulation program to determine the relative proportions of the main food groups in the diet. This was combined with existing knowledge of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ isotopes; calorific content and protein yields of Pacific food types; and geological, archaeological, and metabolic information in order to generate a range of possible food compositions that could have produced the isotope pattern seen. This stochastic model has been used to reconstruct the relative dietary proportions for human remains throughout the tropical Pacific and New Zealand (Leach et al. 2000, 2003).

In this paper, we evaluate the potential of obtaining reliable calibrated ^{14}C results for human bone from the Pacific using dietary information obtained from S, N, and C isotope data, following the methodology of Leach et al. (2000, 2003). To this end, 2 new ^{14}C determinations of human bone gelatin from the burial ground at Watom have been obtained. The dietary-corrected calibrated results are compared to a mixed calibrated age for the bone, which is determined from linear interpolation between $\delta^{13}C$ endpoints (cf. Arneborg et al. 1999). The reliability of all calibrated results are evaluated by comparison with ^{14}C determinations from associated contexts and archaeological evidence.

WATOM

In 1965–7, excavations were undertaken at the SAC site on Watom Island, just off the northeast coast of New Britain (Figure 1). These excavations established the presence of 2 cultural layers buried beneath an ash layer (Zone B). The lower of the 2 cultural deposits (Zone C2) was characterized by the remains of domestic habitation, Late Lapita[1]-style pottery, and fingernail-impressed pottery. A single ^{14}C determination of human bone from Zone C2 was obtained at the time (ANU-37b; 2420 ± 110 BP) (Specht 1968).

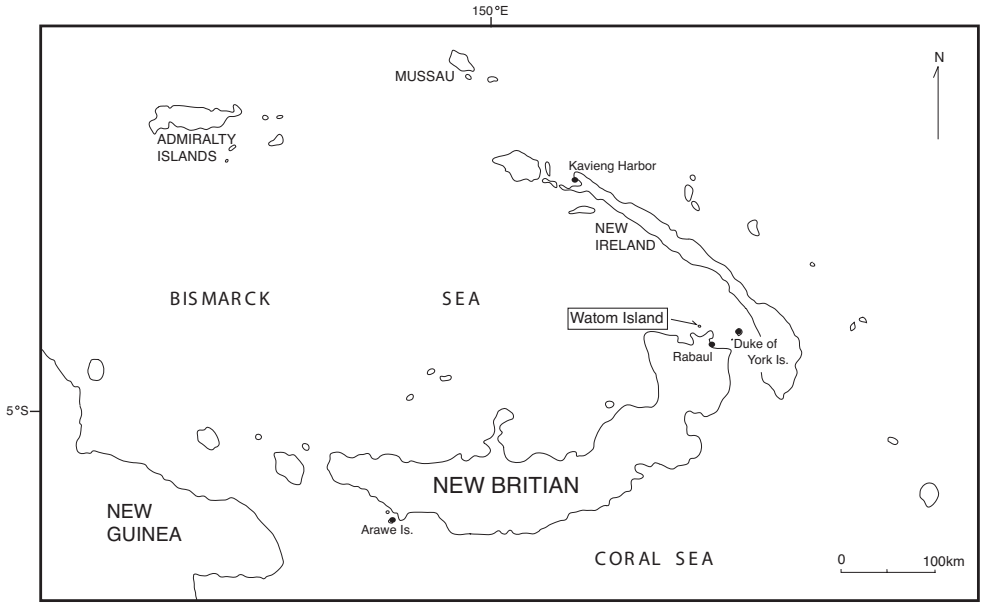

Figure 1 Map of the Bismarck archipelago showing Watom Island and locations mentioned in text

[1]The remains of the Lapita cultural complex stretch from the Bismarck archipelago to Samoa, and are dated to between 3500 BP and 2000 BP (1550–50 BC). Dentate-stamped pottery is one of the more distinctive components of this complex (Green 1979; Spriggs 1996).

Following subsequent excavations in 1985, 2 more ^{14}C determinations on a single *Tridacna* shell sample (ANU-5336 [2530 ± 90 BP] and Beta-16835 [2470 ± 75 BP]) were obtained for Zone C2. This shell was lodged within the infill of a pit (g) under a pile of stones that spilled into the pit and was considered at the time to be associated with the burial deposits (see Green and Anson 2000:43, Figure 8). The 2 dates returned a pooled calibrated result of 2241–2063 BP at 1 σ (291–113 BC) (using a ΔR of 0). A date was also obtained on a sample of *Trochus niloticus* (ANU-5339: 3490 ± 80 BP) recovered from the very basal deposits of SAC. This result was considered to be too old to date Zone C2 given the other ^{14}C results and associated pottery, and was therefore attributed to Zone D (Green and Anson 2000:38–9). Using this data, Green and Anson (2000:46) proposed an event history for the site that began with the formation of a sandbank around 3450–3250 BP (1300–1500 BC) (Zone D). This was followed by a brief Lapita-age domestic occupation inferred to have begun around 2350 BP (400 BC). After a short interval without activity, the site was used as a burial ground around 2250–2050 BP (300–100 BC) (Zone C2), and the area was later reoccupied for domestic purposes in 2100–1900 BP (150 BC–AD 50) (Zone C1).

The attribution of these burials to the Lapita horizon by Green et al. (1989:220)[2] has caused some controversy. Several researchers have expressed doubts about the dating of the site, partly because the burials were considered to be far too young when compared to similar Lapita sites in the region, but also because of uncertainties about the integrity of the deposits (Gosden et al. 1989:563; Spriggs 2001:241; Best 2002:86–9). Recently, analysis of the plant remains at SAC has found no evidence of contamination of Zone C2 by C1 (Lentfer and Green 2003:83), and supports the original excavators' observations that disturbance did not extend between the layers (Green and Anson 2000:84; Specht 2003:132). The reliability of ANU-37b remains in doubt, however, because of the uncertain effect of human diet and unproven relationship to other dated features.

DIETARY INPUT AND THE BURIALS

Stable isotopes of "collagen" (the fraction remaining after digestion of bone with phosphoric acid) have previously been measured from six of the burials found at SAC (Leach et al. 2000). This data was analyzed by a computer simulation program that was designed to estimate the relative proportions of the main food groups in the diet of prehistoric Pacific peoples (Leach et al. 1996). From this data, Leach et al. (2000) concluded that about 64 wt% of the diet was land-based and 36 wt% came from the sea. Moreover, 2.7 wt% of the diet was obtained from C_4 pathway plants (e.g. sugarcane or a herbivore that browsed on the C_4 grasslands) and 6 wt% from reef fish. This hypothesis of a predominantly terrestrial-based diet is supported by trace element analysis (Horward 1988:138) and midden remains that were dominated by pig, with lesser quantities of bandicoot, reptile, and unidentified bird bones (Green and Anson 2000:50–1).

Unfortunately, the human bone ^{14}C determination (ANU-37b) is a mix of material from several of the burials—Burial 1, and possibly burials 2 and 3 (Specht, personal communication, 2002). Dietary variation amongst these individuals has been suggested on the basis of $\delta^{15}N$ and $\delta^{34}S$ isotope values (Leach et al. 2000:151). Moreover, these individuals could have significantly different burial dates. Variation in the burial practices may also support this possibility: Burial 1 was in a fully extended supine position, whereas burials 2 and 3 belong to a second grouping of articulated flexed burials in oval and rounded pits (Specht 1968:126; Green et al. 1989:219).

[2]A few sherds of dentate-stamped ware were discovered in Burial 4 (Green et al. 1989:220). Unfortunately, these sherds could not be used to conclusively date the burial, though some would see such a close association as indicative, given no other source for the pit infill than the pottery-bearing layer into which it was excavated.

The reliability of the original bone ^{14}C determination must also be questioned. When pretreated in 1966, ANU-37b was given an acid wash to remove the carbonate fraction (Robertson, personal communication, 2001). This pretreatment is no longer recommended for most archaeological bone samples because significant contamination can be left following pretreatment, depending on the extent of collagen degradation (van Klinken and Hedges 1995:268). Unfortunately, no analysis of the bone preservation state was made at the time of dating, though it was noted during subsequent excavations that the bones were generally in a poor condition, probably because they were within, or just above, the high tide water table (Green and Anson 2000:46). A high C:N ratio of 3.7 obtained by Leach et al. (2000:152) for Burial 3 also suggests some contamination was not removed by the acid wash pretreatment.[3] Given these uncertainties, it was decided to re-sample and re-date the Watom burials. A separate dating of Burial 3 by another laboratory has also been carried out and will be reported independently of this paper. This result does not provide conflicting evidence of the age of Burial 3.

MATERIAL AND METHOD

We obtained finely powdered bone from burials 1, 2, and 3, which had been held in storage at Otago University in New Zealand. Gelatin was extracted using a modified Longin method (Longin 1971), which is the standard method for pretreating bones at the Waikato Radiocarbon Dating Laboratory (Petchey and Higham 2000). First, the sample was decalcified in 2% w/v HCl at 4 °C for 24 hr, then rinsed with distilled water. This acid insoluble collagen was gelatinized by heating in weakly acidic water (pH = 3 at 90 °C for 4 hr). The supernatant ("gelatin") was then removed and freeze-dried.

All gelatin stable isotope measurements used for dietary reconstruction were made at GV Instruments, England, using a standard EuroVector™ elemental analyzer interfaced directly to the ion source of a stable isotope mass spectrometer (see Leach et al. 2003:43 for details). Graphite targets were processed by the Waikato Radiocarbon Dating Laboratory in New Zealand, by the reduction of CO_2 with Zn in a reaction catalyzed by iron powder at a temperature of about 575 °C. The resulting graphite was compressed into a target for measurement at the Rafter Radiocarbon Laboratory, Lower Hutt, New Zealand.

The stable isotope data was analyzed by a computer simulation program that was designed to estimate the relative proportions of the main food groups in the diet of prehistoric Pacific populations (see Leach et al. 1996 for methodology) (Method 1). The parameters used in this diet simulation are given in Appendix 1. The results were compared to % marine values calculated by linear interpolation using the single isotope option in the program ISOERROR 1.04 (Phillips and Gregg 2001). We selected $\delta^{13}C$ endpoint values of –12‰ for purely marine and –21‰ for purely terrestrial (C_3) diets (after Hobson and Collier [1984] for coastal Queenslanders in Australia) (Method 2).

RESULTS

The success of any bone ^{14}C determination is largely dependent on the preservation state (degree of contamination and degradation) and the pretreatment used to purify and isolate the bone protein. In this instance, the use of several isotopes for dietary reconstruction enabled assessment of the reliability of the data obtained. This is especially important in the Pacific, where hot, humid conditions contribute to rapid bone decay.

Stable isotope and elemental results for burials 1, 2, and 3 are shown in Table 1. Numerous researchers have given guidelines for acceptable "collagen" C and N parameters.[3] All the data collected for the pretreated gelatin from the Watom burials appear to fall within these guidelines. These data can, however, give false positives. Acceptable parameters for sulphur are not as well documented. Rich-

ards et al. (2001:188) state that modern collagen has a C:S ratio of around 780. For burials 1, 2, and 3, we obtained values that are significantly lower than this (C:S values range from 130.5 for Burial 2 to 389.2 for Burial 3) (Table 1). This suggests a significant loss of protein, which is supported by the low percentages of extractable gelatin for the 3 burials. At the Waikato Radiocarbon Dating Laboratory, a gelatin yield of less than 2% is generally considered to be of "poor" preservation. ^{14}C results of such low protein bones may be problematic (Petchey 1998). Only Burial 2 fell below this, with a gelatin yield of 1.17% (Table 1).

Table 1 QC data for gelatin from burials 1, 2, and 3 from Watom.[a]

Sample	% yield gel[b]	$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$	%N	%C	%S	C:S	C:N
B1	2.10	10.9	–18.1	6.5	14.16 ± 0.20	40.55 ± 0.16	0.50 ± 0.02	216.5	3.34
B2	1.17	10.7	–18.5	7.5	13.91 ± 0.10	39.10 ± 0.53	0.80 ± 0.04	130.5	3.28
B3	2.40	11.1	–17.8	10.1	15.08 ± 0.03	42.23 ± 0.32	0.29 ± 0.00	389.2	3.27

[a]$\delta^{13}C$ values were measured relative to the VPDB standard and have errors of ±0.1‰. $\delta^{15}N$ values were measured relative to the AIR standard and have errors of ±0.2‰. $\delta^{34}S$ values were measured relative to the VB5 standard for consistency with Leach et al. (1996, 2003) and have errors of ± 0.5‰. Elemental S concentration is measured relative to the CORN standard (Alpha Resources, P.O. Box 199, Stevensville, Michigan 49127, USA) (Morrison, personal communication, January 2005).

[b]Protein yields were measured as a percentage of the extractable gelatin.

Given these results, we concluded that the gelatin for burials 1 and 3 should be well enough preserved for dietary reconstruction and ^{14}C dating.

CALIBRATION AND DIET

The $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values used for probable diet reconstruction are given in Table 1. ^{14}C data for the burials are shown in Table 2 along with the probable % marine contribution to the diets as determined using the 2 methods listed above. Details of the diet composition results obtained using the Leach et al. (1996) computer simulation program and all 3 isotopes (Method 1) are given in Appendix 2. Linear interpolation from $\delta^{13}C$ endpoints (Method 2) tends to give a slightly higher marine contribution than the value obtained from Method 1. The greatest difference was recorded for Burial 1, which has a probable 19 wt% marine contribution using Method 1 compared to 32 wt% for Method 2. A higher wt% marine for Method 2 may be due to the inclusion of C_4 foods in the diet, which would result in a more positive $\delta^{13}C$ signature. The % marine contribution for burials 2 and 3 are similar using both methods (see Table 2).

Table 2 Results of ^{14}C and stable isotope analyses.

Lab nr	Burial	^{14}C age ± std. error	$\delta^{13}C$ (‰) (fractionation correction)[a]	% Marine (C:N:S) Method 1	% Marine ($\delta^{13}C$) Method 2
Wk-15567	1	2757 ± 32 BP	–17.97 ± 0.2	19	32
—	2	—	—	22	28
Wk-15568	3	2633 ± 33 BP	–17.69 ± 0.2	37	35

[a]$\delta^{13}C$ value used to correct for vacuum line fractionation. Measurement carried out at the Stable Isotope Unit, University of Waikato.

[3]Modern collagen has about 43% carbon and 16% nitrogen and should have a C:N value of about 3.2 (Ambrose and Norr 1993:403). Using data compiled from the Oxford University Radiocarbon Accelerator Unit, van Klinken (1999:691) suggested that most well-preserved archaeological bone protein ranges between 11 and 16% N, with an average of 35% C and a C:N ratio range of 3.1–3.5.

The human bone determinations were calibrated using the mixed calibration option in OxCal v 3.10 (Bronk Ramsey 1995, 2001). This program calculates the calibration curve valid for a given fraction of marine food by linear interpolation between the terrestrial calibration curve of Reimer et al. (2004) and the marine curve of Hughen et al. (2004). We have used an uncertainty of ±10% for the diet correction, following the recommendations of Ambrose (1993:112), and a reservoir correction (ΔR) of 261 ± 101 yr for Watom in order to adjust for regional oceanic variation in ^{14}C (Petchey, unpublished data). To evaluate the difference between the 2 dietary calibration models, ^{14}C determinations are calibrated, combined, and then assessed in light of the combined data. <*An* is the value (dependent on *n*) below which the agreement index (*A*) should not fall (Bronk Ramsey 1995).

Figure 2 shows the calibrated age ranges for Burial 1 (Wk-15567: 2757 ± 32 BP) and Burial 3 (Wk-15568: 2633 ± 33 BP). The results are compared to published ^{14}C dates from zones C2 and C1. The calibrated age range for Burial 1 with a 19 wt% marine contribution (Method 1) is 2850–2720 BP at 1 σ (900–770 BC) compared to 2760–2660, 2640–2610, and 2600–2510 BP at 1 σ (810–710, 690–660, and 650–560 BC) for a 32 wt% marine contribution (Method 2). These 2 results are in good agreement (n = 2; A = 118.0 [<An = 50.0%]). For Burial 3, the calibrated age range for Method 1 (37 wt%) is 2670–2630, 2620–2590, and 2540–2350 BP at 1 σ (720–680, 670–640, and 590–380 BC) compared to 2670–2630, 2620–2590, and 2550–2350 BP at 1 σ (720–680, 670–640, and 600–400 BC) for Method 2 (35 wt%). Again, the results of the 2 methods are almost identical (n = 2; A = 110.5 [<An = 50.0%]).

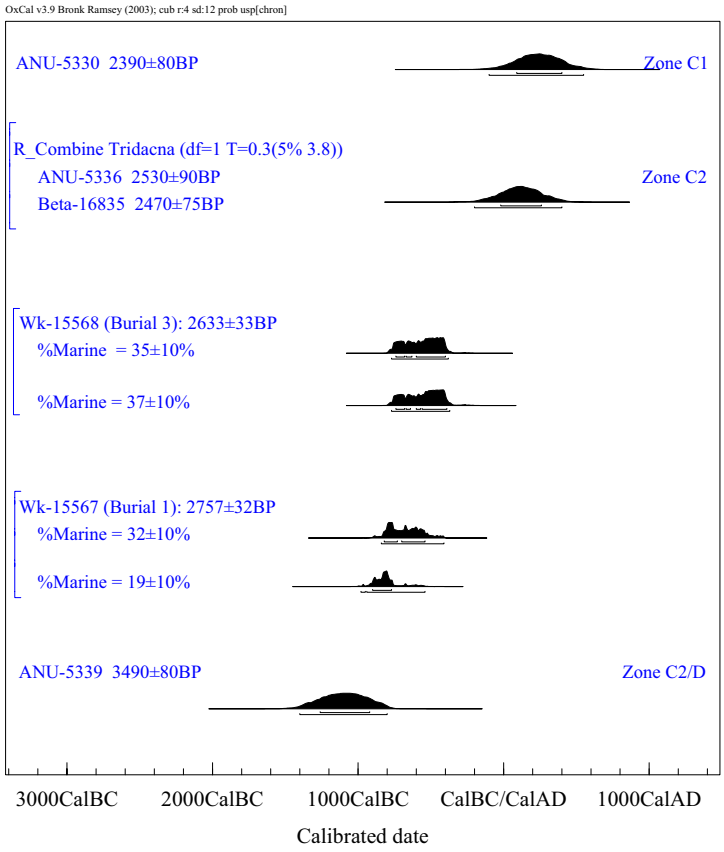

Figure 2 Calibrated ^{14}C determinations from zones C1 and C2, SAC, Watom Island. Error bars show 1- and 2-σ deviations.

DISCUSSION

Neither the use of 3 isotopes (Method 1) nor the linear interpolation from $\delta^{13}C$ endpoints (Method 2) resulted in calibrated age ranges that were statistically different. In this instance, it is impossible to decide which method is better for calibrating bone samples. However, in areas where reef or C_4 foods play a greater role this variance may increase. Unfortunately, available isotope data from Pacific food sources is limited, and the interpretation of dietary input from isotopes is a highly complex area with numerous assumptions. Variation has been attributed to climate (Heaton et al. 1986; Ambrose 1993; van Klinken et al. 1994; Richards and van Klinken 1997; Cook et al. 2002); geographical location (Hobson 1999; Pate et al. 2002; Kelly 2000); the effect of aridity, salinity, inadequate diet (Heaton 1987; Hobson and Clark 1992; Ambrose 1993); and disease (Bayliss et al. 2004). The impact of diet to tissue fractionation is also unresolved (Ambrose and Norr 1993; Tieszen and Fagre 1993; Fogel and Tuross 2003).

Despite these limitations, this research has had several unexpected outcomes. First, the results from burials 1 and 3 are significantly older than the previous date obtained for the burials (ANU-37b; 2420 ± 110 BP). This supports our suggestion above that the simple acid wash pretreatment used in 1966 to isolate the bone protein was not sufficient to remove contamination from ANU-37b. Second, these results lend support to the presence of a slightly older Lapita settlement elsewhere on Watom Island, possibly further inland as speculated by Specht (2003:125), and make it highly probable that ANU-5339 was a food shell from an initial occupation of the beach around 3210–2870 cal BP at 1 σ (1260–920 BC) and was not associated with Zone D. This calibrated result is younger than previously thought because of the application of the new Watom ΔR value (261 ± 101 yr) instead of zero (see Figure 2). Third, these results are also much older than the recalibrated shell dates ANU-5336 (2050–1700 cal BP at 1 σ [100 BC–AD 250]) and Beta-16835 (1970–1650 cal BP at 1 σ [20 BC–AD 300]) of a single shell from under a pile of stones in the infill of the pit (g) (see Green and Anson 2000:43, Figure 8).[4] Green and Anson (2000:45) had used the ^{14}C result for ANU-37b and the fact that the dated stone pile seemed to be part of an alignment that delineated the burial area, to suggest that they were contemporary. This relationship is now open to debate and it seems likely that Zone C2 covers a more extensive sequence of occupation than previously thought.

A total of 8 burials have been recovered from Watom SAC. It is evident that there was some initial activity prior to the interment of burials 2 and 5, and several of the burial pits could be traced in the section well up into Zone C2, indicating that some depth of deposit had accumulated by the time they were dug (there is no information for burials 1 and 3) (Green and Anson 2000:45). Moreover, Burial 8 was cut by burials 1 and 4, and must therefore be older than both. Similarly, Specht (1968) thought that Burial 2 had been disturbed by the placement of Burial 3. This suggests that neither Burial 1 nor Burial 3 represents the earliest interment activity. Unfortunately, none of the burials have been cut by features that enable a clear sequence of events to be demonstrated. It remains possible, therefore, that the burial ground was in intermittent use for several centuries, a fact that may explain differences in burial practice (see Green et al. 1989:219), though the ^{14}C results for the extended supine Burial 1 and articulated flexed Burial 3 do not support significant differences in age for different burial types. Unfortunately, the only way to currently date the remaining burials is to obtain ^{14}C determinations on the bone, but the flatness of the calibration curve around 2400–2700 yr ago exaggerates the spread in calibrated age range and limits the resolution of the ^{14}C data.

[4]Subsequent re-dating of features within zones C1 and C2 at SAC has confirmed the reliability of all shell ^{14}C results, including ANU-5339 (Petchey, unpublished data).

From a wider perspective, these new bone dates are closer in age to the result obtained for the basal layer (Zone C4)[5] at the nearby site of SDI, which Anson (2000:133) suggested should be of similar age to SAC, Zone C2 on the basis of ceramic motif similarities. These results also place the burial deposits closer in age to sites with similar Lapita assemblages in the Bismarck archipelago (e.g. SDP, SEE, and SET from the Duke of York Islands; and FOH, FOL, and FOJ from the Arawe Islands [Gosden et al. 1989; Summerhayes 2001]).

Other Uncertainties

It is well documented that Lapita populations were seafairing people with well-developed trade links (Green 1996). Evidence from Watom suggests that these individuals were no different, and obsidian recovered from the SAC site has been identified as coming as far away as the Admiralty Islands (540 km away) (Green and Anson 2000:66–7). The possibility that these individuals traveled significantly during their lifetimes places some doubt on the reliability of the ΔR used in this paper. Petchey et al. (2004) noted that ΔR from the SW Pacific region tended to be highly variable, which they attributed to intermittent upwelling of depleted ^{14}C in response to major current reversals during the monsoons. This may be manifest in the ΔR values from Kavieng Harbor in New Ireland, which range from 508 ± 60 yr to 298 ± 50 yr. In contrast, ΔR values from the Coral Sea (southeast coast of New Britain) are much lower, and Petchey et al. (2004) suggest that currents originating from here influence the ΔR for the Duke of York Islands (ΔR = 39 ± 68 yr), less than 40 km from Watom Island. No information is available for the southwest coast of New Britain, though we think it is likely that this region is also influenced by low ΔR values from the Coral Sea. Moreover, ΔR results on pre-1950 shells collected from Rabaul Harbor, 20 km from Watom, indicate a wide range of values (Petchey, unpublished data), some of which predate the creation of the caldera that forms the harbor (approximately 1400 BP) and are likely to be influenced by volcanic activity. This identified range in ΔR could further limit the resolution of ^{14}C determinations of both shell and human bone from Watom and other sites in this region.

CONCLUSION

Two new human bone ^{14}C determinations have been obtained for burials 1 and 3 from SAC on Watom Island. $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ data have been used to apply a correction to these dates for the consumption of different foods. Although the influence of marine foods on the ^{14}C calibration is significant, the impact of other food types in this instance is negligible. We recommend that human bone determinations from the Pacific must have $\delta^{13}C$ and $\delta^{15}N$ isotopes measured in order to obtain reliable calibrations. The use of a third isotope, $\delta^{34}S$, is recommended where C_4 and reef foods make up a significant portion of the diet. Moreover, all bones from Pacific archaeological sites should have a minimum gelatin pretreatment and be assessed for degradation and contamination prior to dating. Currently, our ability to obtain usable human bone calibrated dates is influenced more by the availability of accurate marine offsets (ΔR) and the removal of contamination during pretreatment than by the exactness of dietary reconstruction.

These 2 new gelatin determinations place the age of burials 1 and 3 within the first half of the 1st millennium BC. These results are significantly older than previous assessments for the burials and necessitate a reassessment of the chronology of later features within Zone C2 at the SAC site and the relationship of this burial ground to Lapita sites elsewhere in the Bismarck archipelago.

[5]Beta-16836 (3020 ± 90 BP; *Tridacna* sp.) has a calibrated age of 2670–2330 BP at 1 σ (720–380 BC) when calibrated with a ΔR of 261 ± 101 yr.

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APPENDIX 1: PARAMETERS USED FOR DIET SIMULATION OF WATOM BURIAL DATA

- Range of acceptable energy consumption: 1800.0 to 3700.0 kcal per day
- Range of acceptable protein consumption: 25.0 to 200.0 g per day
- Isotope offsets from food to collagen:
  $\delta^{13}C$ +5.0
  $\delta^{15}N$ +3.0
  $\delta^{34}S$ –0.5 for land foods
  $\delta^{34}S$ –0.9 for marine foods

Appendix 1a Mean values for each food.

Food	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	Protein g/100 g	kcal g/100 g
1 = C_3 plants	–26.0	5.8	4.9	2.2	145.0
2 = C_4 plants	–11.5	10.0	4.9	0.4	38.0
3 = Land herbivores	–22.6	5.4	4.4	23.1	155.0
4 = Marine shellfish	–14.0	7.2	18.6	12.9	69.0
5 = Coral reef fish	–12.6	7.9	17.7	19.7	100.0
6 = Non-reef fish	–16.5	14	17.7	19.7	100.0
7 = Marine mammals[a]	–16.8	15.7	16.8	14.0	262.0

[a]It is assumed that marine mammals did not contribute to Watom diet (see Leach et al. 2000:151).

Appendix 1b Population isotope values and tolerance values for testing.

Isotope	Burial 1	Burial 2	Burial 3
$\delta^{13}C$	–18.1	–18.5	–17.8
$\delta^{15}N$	10.9	10.7	11.1
$\delta^{34}S$	6.5	7.5	10.1
Tolerance			
$\delta^{13}C$	1.0	1.2	2.0
$\delta^{15}N$	1.5	1.2	1.5
$\delta^{34}S$	1.5	1.2	1.5

APPENDIX 2: WATOM DIET COMPOSITION FROM COMPUTER SIMULATIONS

Appendix 2: Watom diet composition.[a,b]

	Burial 1		Burial 2		Burial 3	
	Mean	SD	Mean	SD	Mean	SD
Energy kcal/day	2414.1	484.0	2449.2	483.5	2152.3	294.9
Protein g/day	156.9	30.4	155.9	29.3	173.0	20.0
$\delta^{13}C$	–17.5	0.4	–17.6	0.3	–16.2	0.3
$\delta^{15}N$	9.9	0.3	10.0	0.4	10.7	0.7
$\delta^{34}S$	6.7	0.7	7.1	0.5	9.0	0.4
Food weight %						
C_3 plants	57.8	9.6	60.3	8.8	49.8	6.6
C_4 plants	5.4	3.9	3.5	2.6	2.8	2.1
Land herbivores	18.2	11.4	14.7	10.4	10.3	7.2
Marine shellfish	5.0	4.1	5.5	4.2	11.3	7.7
Coral reef fish	4.5	3.8	4.7	3.8	7.0	6.0
Non-reef fish	9.1	5.1	11.4	5.2	18.7	9.4
Marine mammals	0.0	0.0	0.0	0.0	0.0	0.0
Protein g/day						
C_3 plants	24.01	8.19	25.24	7.89	19.47	4.91
C_4 plants	0.42	0.35	0.27	0.24	0.20	0.17
Land herbivores	71.29	38.30	57.93	35.40	39.36	25.12
Marine shellfish	12.30	11.16	13.62	11.50	26.49	19.97
Coral reef fish	16.58	15.01	17.36	15.14	24.33	21.08
Non-reef fish	32.28	19.06	41.49	20.32	63.16	31.13
Marine mammals	0.0	0.0	0.0	0.0	0.0	0.0
Energy kcal/day						
C_3 plants	1582.21	539.74	1663.23	520.27	1283.27	323.88
C_4 plants	39.66	33.54	25.65	22.35	19.17	15.69
Land herbivores	478.38	256.99	388.74	237.53	264.09	168.52
Marine shellfish	65.80	59.68	72.87	61.51	141.67	106.84
Coral reef fish	84.19	76.17	88.13	76.84	123.48	106.98
Non-reef fish	163.86	96.73	210.62	103.13	320.61	158.03
Marine mammals	0.0	0.0	0.0	0.0	0.0	0.0

[a]Total number of simulations attempted: 31,968,404 (Burial 3); 157,338,945 (Burial 2); 49,437,707 (Burial 1).
[b]Number of successful simulations: 5024 (Burial 3); 10,180 (Burial 2); 6850 (Burial 1).